

LTA STRUCTURES AND MATERIALS TECHNOLOGY

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ABSTRACT: The state-of-the-art concerning structures and materials technology is reviewed. It is shown that many present materials developments resulting from balloon and aircraft research programs can be applied to new concepts in LTA vehicles. Both buoyant and semi-buoyant vehicles will utilize similar approaches to solving structural problems and could involve pressurized non-rigid and unpressurized rigid structures. System designs common to both and vital to structural integrity will include much of the past technology as well. Further research is needed in determination of structural loads, especially in future design concepts.

INTRODUCTION

History records that the Western civilized world discovered the principle of balloon flight when Joseph Montgolfier fashioned a cubical container from an innkeeper's skirt of silk taffeta in November 1782 to capture the smoke and heated air of the fireplace and watched the device rise to the ceiling.

It was common sense on the part of Joseph and Etienne Montgolfier that the container or envelope holding the gases had to be a light-weight material. Later versions of Montgolfier balloons were made of paper or lined with it. Varnished silk was selected for hydrogen balloons and was a favorite among balloonists many years. As with most successful inventions, the specialized industries soon became

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interested enough to apply their particular knowledge and skills to the production of more suitable materials, such as high quality cotton fabric and rubber coatings.

The development of the airship forced the injection of engineering into the subject. The inefficiency of propulsion systems accounted for such a great portion of the available lift for power plants that designers (be they professional or amateurs) were compelled to utilize lightweight structural design techniques to achieve any useful lift at all. When airships passed from the category of inventor's brainchild and from sport vehicles to transportation or military vehicles of useful potential, funds and personnel became available to incorporate engineering approaches into designs. Likewise, as with balloons, the input of other specialists and industries also began to be a part of improving the vehicle and increasing its efficiency. Much can be written concerning the historical aspect of the development itself. However, this paper will primarily confine itself to a review of current technology and specifically to the state of the art in two major disciplines - materials and structures.

MATERIALS AND STRUCTURES TECHNOLOGY

These two disciplines are so interrelated that it is difficult, if not impossible, to clearly separate one from the other. Structural design techniques vary according to the materials chosen or available. Materials are chosen depending on the structural design approach to be used. Modern design practices produce synergistic effects when structures and materials are properly related.

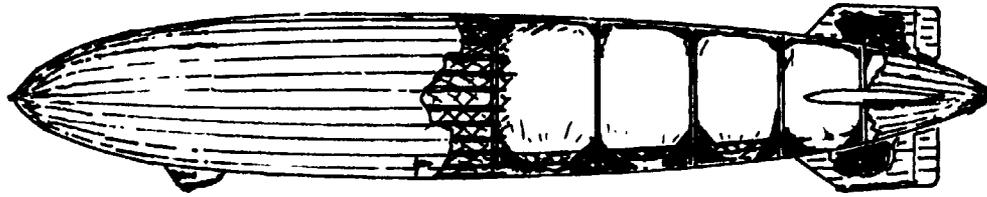
Recent thought on the subject of airships indicates that future vehicles could consist of configurations vastly different from vehicles present or past. It has been shown by various studies (Ref. 1, 2, 3, and 4) that airships which combine dynamic and static lift (hybrids) may offer an improvement in efficiency in certain speed ranges. It has also been proposed that either conventional or hybrid airships employing heated air or other gases may also show advantages for certain missions (Ref. 4, 5, and 6).

As long as such vehicles require buoyancy or static lift for any part of their mission, there will be certain features common to all in terms of structural and material requirements. These stem from the fact that buoyancy of any usable amount requires large displacement. Thus, all LTA aircraft or their variations will be large vehicles always exceeding in size any of their HTA counterparts by at least several factors.

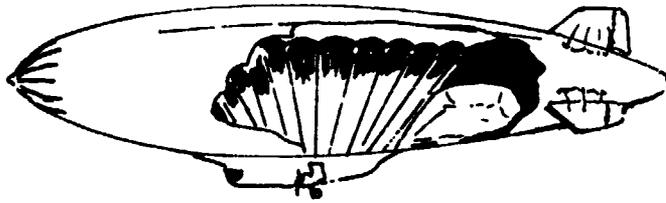
Large size or volume is accompanied by large surface area on which unit air loads are low and much lower than normal airplane surfaces carry. Ultra-lightweight structural design is required to provide the external contours of such vehicles without sacrificing lifting efficiency. Thus, the need for fabrics, lightweight high-stiffness structural members, etc. is well established. Minimum material gage is often a problem in design and construction.

The containment of any gas requires use of pressure control systems capable of handling high rates of gas flow in order to preserve structural integrity. Such requirements are reflected in sub-system development of valves, blowers, and in the design of gas shafts, air ducts, etc., which require application of special materials and design techniques.

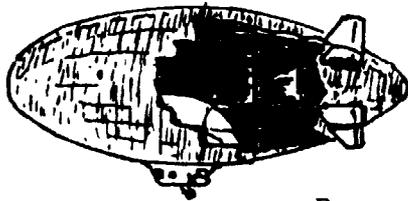
AIRSHIP STRUCTURAL TYPES



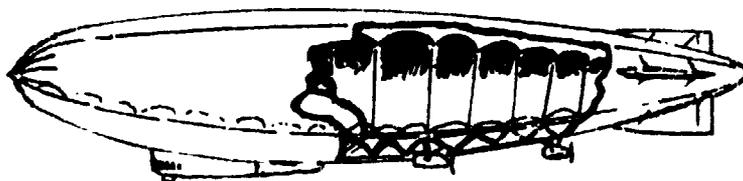
Non-pressure rigid



Pressure non-rigid



Pressure rigid



Pressure semi-rigid

Figure 1

Regardless of vehicle type (conventional or hybrid), the designer has to choose whether to maintain an aerodynamic configuration by means of pressure or by means of a non-pressurized external skin supported by an internal rigid structure, or by a combination of both. Figure 1 illustrates airships which are examples of the various types.

These common characteristics distinguish LTA vehicles from their HTA contemporaries and require application of a considerable amount of past knowledge as well as new technology.

Materials

Pliant Materials - As noted above, airships are pressure sensitive vehicles. Therefore, there is usually a need for at least part of the gas container to be capable of volume changes and be constructed of a pliant material.

An ideal material in this category would be a film with extremely low permeability, high tensile strength, high tear strength, a linear stress-strain curve to the yield point, reasonable Young's tensile modulus, good ductility, isotropic character, and stable properties under expected environmental conditions. Thus far no such material exists.

High altitude scientific balloons have used films alone for envelopes. Such balloons are an example of the interdependence of structures and materials. During the 1950's a balloon form was developed known as the natural shape. The contour of the envelope was determined by the gas head pressure and resulted in all stresses being carried in the vertical direction such that theoretically there would be zero circumferential (parallel to equator) tension. Such design enabled use of oriented polyethylene and later use of vertical load tapes.

One parameter peculiar to balloons of this type, which does not necessarily apply in the case of airships, is that of the high altitude environment. In such an environment, the envelope is directly exposed to very low temperature and high ultraviolet radiation.

Higher strength films are obtained by reinforcing with some kind of filament, usually bonded to the film and oriented in a quasi-orthotropic pattern. Table 1 lists a few examples of films and their characteristics for balloons and gas cells. For comparison, older film and gas cell materials are also listed.

Table 1

BALLOON FILMS AND GAS CELL MATERIALS

| <u>FILM</u> | <u>Reinforcement</u> | <u>Weight</u> | <u>Tensile Strength</u> | <u>Permeability</u> |
|--------------------|----------------------|----------------------------|-------------------------|------------------------|
| | | <u>Oz./Yd.²</u> | <u>Lbs./In. Warp</u> | <u>L/m²</u> |
| Polyethylene | None | 0.3 | 15 | 1.00 |
| 2 Ply Mylar | None | 1.6 | 30 | 0.30 |
| Mylar | Dacron Scrim | 1.6 | 45 | 1.75 |
| Nylon | Nylon Cloth | 1.9 | 50 | 2.00 |
| Rubber | Cotton | 5.5 | 45 | 3.00 |
| Coating | | | | |
| Gold Beater's Skin | Cotton | 4.5 | 40 | 2.00 |

Many of these materials are of interest for airship applications. One significant characteristic sometimes not considered at the outset, is that of resistance to manufacturing and handling damage and resistance to tearing. Films tear easily. Reinforced films are much more difficult to tear once the damage reaches the reinforcing filaments.

If the material is to be used as a gas container primarily, its required strength would be determined by the amount of superpressure it would have to endure and the method of transferring the lift of the gas to the structure. These requirements would combine with the anticipated cyclic variations of pressure and flexing, atmospheric conditions, and the above mentioned resistance to accidental damage. It is anticipated that future airship gas cells would be similar to the reinforced balloon films now in use.

When material is required to serve as hull structure as well as gas container, as in a non-rigid airship, strength and other requirements are considerably more severe. The stresses are higher, the environmental effects are a major factor, and gas retention becomes a serious problem. These parameters combine to exceed the properties of films alone and thus far, only the higher efficiencies obtainable from closely spaced filamentary materials such as textiles, appear to be satisfactory.

Textiles have been conventionally woven as two sets of threads crossing each other in an orthogonal pattern. Such weaves are effective in transmitting stress in their respective directions, but not in any diagonal direction, i.e. on the bias. Therefore, the usual solution is to bond two or more plies of cloth together such that one is oriented 45° to the other. Most two-ply envelopes are constructed in this fashion.

A recent patented textile development, known as "Doweave", provides for this function by having three thread sets intermeshed in a single fabric to provide quasi-isotropic properties and eliminate the need for bonding two or more plies together, therefore making possible single ply envelopes.

Woven fabrics must be coated with an elastomeric material or bonded to a film of sufficient thickness to prevent high gas loss. All non-rigid airships built to date have employed the first method - namely a coating as the gas barrier. For two or more ply construction, the bonding of the fabrics is also accomplished by an elastomeric coating. An outer coating, often of different material from the inner, is applied to the surface exposed to the airstream to provide resistance to and control of environmental effects. The net result of such construction is a material which consists of about half cloth and half elastomer.

If a Doweave type material is used, there is a weight saving of one thread set plus the additional inter-ply elastomer or adhesive. However, since the total elastomeric thickness provides the gas barrier, and a certain minimum amount is required to achieve a given rate of permeability, only specific testing would determine how much could be eliminated totally.

Another approach which theoretically provides more efficiency is to combine the best properties of two materials - namely film and cloth. Thin film can be manufactured to provide a much less porous surface than can be obtained by an equal weight of elastomer. Research programs for improved balloon films have progressively enabled film

manufacturers to achieve unusually thin gages of high quality. For applications where the film is only a gas barrier, the minimum gage theoretically would only be limited by that required to eliminate microscopic holes, and obtain a given rate of permeability. Thus, a weight saving is possible by bonding a film to one or more plies of cloth, and ideally could consist of a combination of the three ply Doweave with a thin film gas barrier.

Fabrics which function as structures undergo a considerable number of cycles of flexing which consists of elongation of the yarns, an interaction of the yarns due to crimp through the interstices, and ply deformation due to shear stresses. All of this flexing has an effect on the bonds between the elastomer or films and the yarns in the cloth. In the case of the former, microscopic paths for gas escape are developed. In the case of films, localized debonding can occur which eventually leads to leaks.

Since envelopes (and gas cells) are manufactured, shipped, and handled many times during both processes, they are subjected to wrinkling, creasing, scuffing, or abraiding conditions. Both elastomeric coatings and films are adversely affected by this treatment. Again, the elastomer can be damaged by the local flexing and the film can be debonded. A number of tests simulating such conditions are usually necessary to evaluate particular candidate materials.

Pliant materials which function as both gas cells and airship hulls must have, in addition to good gas retention, and the other characteristics noted previously, sufficient resistance to creep-rupture under both constant and varying stress. Most materials will creep under constant stress above certain temperatures. Fibers made from either natural or synthetic materials creep at temperatures within the normal operating ranges. The rate of creep varies with the stress level. For a given stress level, a fiber or cloth made from it will fail after a period of time of sustained stress. Envelope materials are chosen on the basis that the failure point is beyond the planned life of the envelope. Since these characteristics vary considerably among various materials, data must be developed or available for each candidate material.

The stress-strain curve for most of the candidate organic fibers shows a linear portion at lower stresses and non-linear portions at higher stresses. Materials which show no linearity are not acceptable for airship envelopes. Uncontrolled stretch results in distortion of the envelope shape which affects the aerodynamic performance of the airship. It also produces severe problems with the rigid components which are attached to the envelope such as nose stiffening, suspension systems, cars, fins, and control systems. This is the reason why nylon has not been used, although it possesses good tensile strength. Polyester fabrics, such as Dacron, on the other hand, do demonstrate satisfactory elongation and creep, and are standard for most airships (and tethered balloons) at present.

In recent years, a new polymeric fiber has been developed by DuPont which appears to be ideal for airship applications. This is called Kevlar-49. It possesses a tensile strength of about 400,000 p.s.i. and higher (580,000 p.s.i. in short lengths). Ref. 7. In addition to its high tensile strength, it has a tensile modulus about double that of aluminum, and a linear stress-strain curve. It is already being applied to aircraft structures as a composite material as will be noted later. As a textile replacement for present airship fabrics, it appears to be a promising candidate. Table 2 compares various natural and synthetic fibers for pressure airship envelopes.

As noted, the concept of using heated gas in certain future vehicles has been proposed. The lifting efficiency of such vehicles varies with the temperature of the gas. If envelope fabrics are required to operate at sustained high ΔT values, these parameters must be factored into the selection and evaluation of the material, particularly with regard to creep and operating life.

Table 2

FIBERS FOR PRESSURE AIRSHIP ENVELOPES

| <u>Fiber</u> | <u>Specific Tensile Strength</u> | <u>Specific Tensile Modulus</u> |
|--------------|----------------------------------|---------------------------------|
| KEVLAR 49 | 8×10^6 | 380×10^6 |
| POLYESTER | 2×10^6 | 20×10^6 |
| NYLON | 2.8×10^6 | 20×10^6 |
| COTTON | 0.8×10^6 | 19×10^6 |
| SILK | 1.0×10^6 | 21×10^6 |

Metals - Modern aluminum alloys have about double the tensile strength of the alloys used during the early 1930's for large airships. While such difference can be translated into weight saving, the percentage is strongly dependent on the application. When applied to a rigid pressure airship design, such as a metalclad, the full improvement in strength may be utilized over the major sections of the hull, provided the airship is large enough. In rigid designs, where girders and frames were employed with a non-structural covering, an 18% weight improvement due mostly to improved girder design has been estimated (Ref. 8).

A significant feature of conventional airship structure is the fact that large portions operate at very low stress. As discussed later, both the Zeppelin types and the pressure types tend to behave as monocoque cylinders in bending and are much more sensitive to the maintenance of adequate structural stiffness against both local and general buckling. Unfortunately, although tensile strength has improved for aluminum alloys, the modulus of elasticity has not. This factor points to the need for localized stiffening of structural members such as may be obtained through application of selective composite reinforcement as discussed later.

Other Metals - The combined requirements for high modulus, good fatigue life, and low corrosion were recognized in design of large airships in the past, and as recently as 1939 stainless steel girders were considered as candidates for airship structural members (Ref. 9). Today, they would continue to be examined, especially in combination with some of the structural design approaches discussed later. Titanium alloys could also provide some of the structure for certain airship hulls. Both stainless steel and titanium would represent higher cost as compared with aluminum, and neither would represent much gain in weight savings, especially in a minimum gage application.

Composite Materials - Fortunately, much of the technology presently being developed and available in connection with the use of composite materials in airplanes can be applied to airships. Table 3 lists the properties available from composites as compared with metals.

Table 3

PROPERTIES OF STRUCTURAL MATERIALS

| <u>Material</u> | <u>Specific Tensile Strength</u> | <u>Specific Tensile Modulus</u> |
|-----------------|----------------------------------|---------------------------------|
| 7075 ALUMINUM | 0.8×10^6 | 100×10^6 |
| 6Al 4V TITANIUM | 1.1×10^6 | 100×10^6 |
| KEVLAR/EPOXY | 3.2×10^6 | 220×10^6 |
| GRAPHITE/EPOXY | 3.5×10^6 | $350-700 \times 10^6$ |

In this regard, two approaches are possible. The first involves the use of composites to provide local strengthening and stiffening of conventional metal structures. This process is described in Ref. 10. Essentially, it consists of bonding laminates made of advanced composite materials (boron or graphite/epoxy) to the surface of structural members, usually stiffeners or flanges located at the maximum radii of gyration in a section of structure. Laminates are manufactured from standard tapes of composite materials. This process could be applied to light alloy members of airships with very effective results.

The second approach would be use of an all-composite structure where all structural members are manufactured from fibrous composite materials. As will be discussed later, the maximum values of weight savings could be obtained from this approach.

Structures

One of the most controversial aspects of past designs and present airship proposals stems from an evaluation of their structural adequacy. In some respects, much of this controversy is the result of comparing past technology in airships with present technology in other aircraft. It is a matter of record that in the period represented by early Zeppelin construction through that of the U.S. rigid airship program (1900-1935) that some of the best aeronautical engineering talent available was associated with airship technology development. The airship structure particularly represented a challenge to the theoretician and analyst and the airship itself was a very advanced aeronautical development. Structural design, therefore, was at its best when applied to the airship. In particular, this refers to the rigid types, since in the case of the pressure types the sizes were smaller, and the problems simpler.

A survey of the state of the art can be made concerning three aspects: loads, structural analysis, and testing.

Loads - Airship hull loads resulting from aerodynamic forces consist of maneuvering loads, gust loads, and ground handling loads.

For airships flying at speeds approaching 100 mph, the hull bending moments produced by flight through gusts by far exceed those from maneuvering. Generally, a thorough analysis of this condition would include determination of loads for the hull itself for a maximum design velocity gust transit, and other conditions which would produce maximum loads on the empennage and other components.

The response of an airship to such conditions is dependent on its configuration and its accompanying dynamic and control characteristics.

Up to and following the design of the Akron and Macon rigid airships, a substantial amount of research was performed to determine maximum gust conditions and airship flight characteristics in gusts. These were limited to the ellipsoidal hull shapes employed for all airships up to the present.

During the 1930's, a special airship research facility became available in Akron, Ohio which contained, among other things, whirling arms, a vertical wind tunnel, and a water channel. These three pieces of apparatus were used in combination with scale models to investigate gust effects on rigid airships. Figures 2 and 3 illustrate two methods used.

The difficulties and uncertainties of relating such tests to full scale results can be appreciated. More significant, however, is the necessity of building a step-by-step base of technology which eventually is proven sound enough to furnish confidence for future design approaches. Since gust response is configuration sensitive, a period of learning and confidence would be necessary for new concepts which represent significant departures from the ellipsoidal form.

Another approach to this problem can be taken by means of a computerized analysis to simulate flight in turbulence. Such studies were initiated in 1958 as part of the U.S. Navy airship structures research program (Ref. 11). Figure 4 shows a typical set of curves obtained in this manner for a large non-rigid airship.

Ground handling of airships has always represented a critical part of the operational cycle. A good case can be made for never hanging or docking airships because the records show more losses or damage occurred in this part of the operation than from any flight accident. The main reason, of course, is the fact that the maximum hull forces used for design are derived from flight conditions as discussed above. Ground forces are only permitted to develop loads which do not exceed flight values. This results in maximum cross winds of about 20 knots against which the airship may be held. If provisions were made for higher winds, the ground condition would become the dominant hull design condition and would result in excess strength (and weight) for flight. Designers have been unwilling to accept this penalty for a non-flight condition.

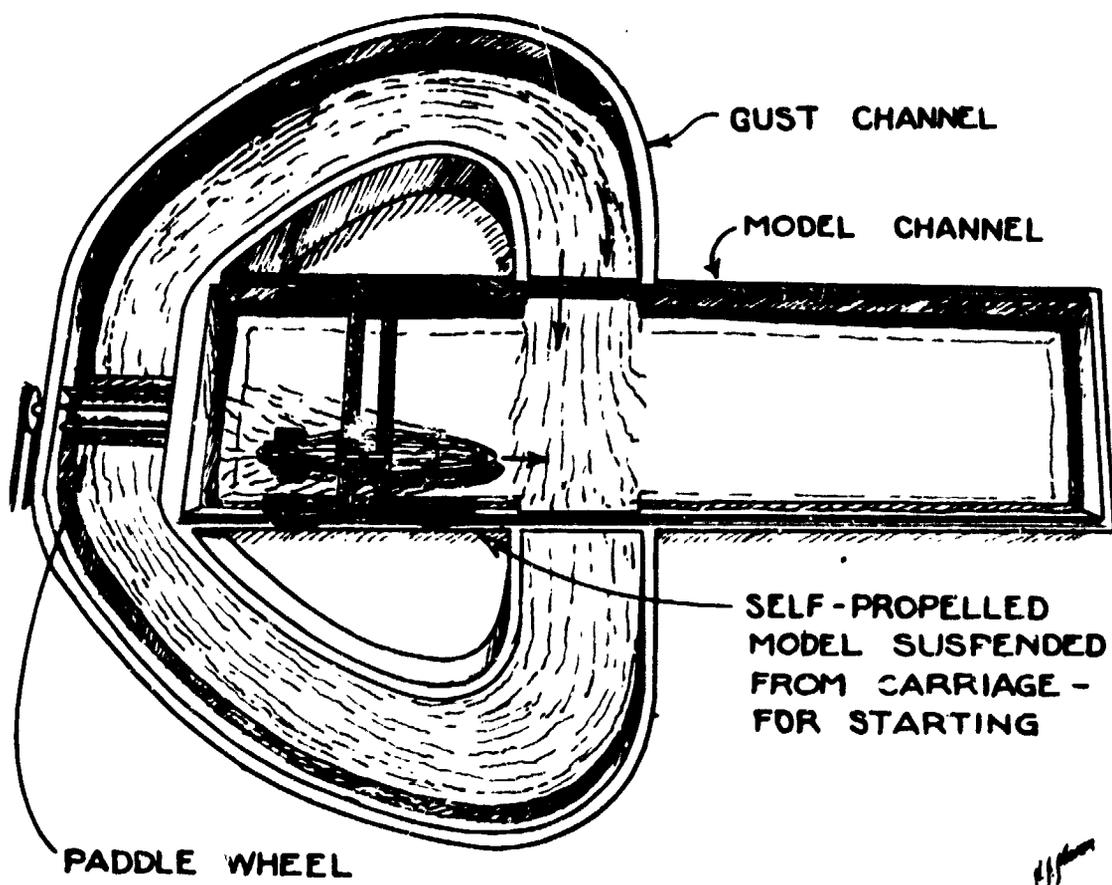
During ground handling operations, lines are designed to slip (if on winches) or part to avoid hull overstress and resultant structural damage. If this should occur in the vicinity of a hangar, the result is a collision and severe damage to the airship.

A number of tests using towed models in water have been run to investigate both the static and dynamic conditions involved. One series of tests actually simulated the complete docking/undocking operation, including the weathervaning motions while moored (Ref. 12).

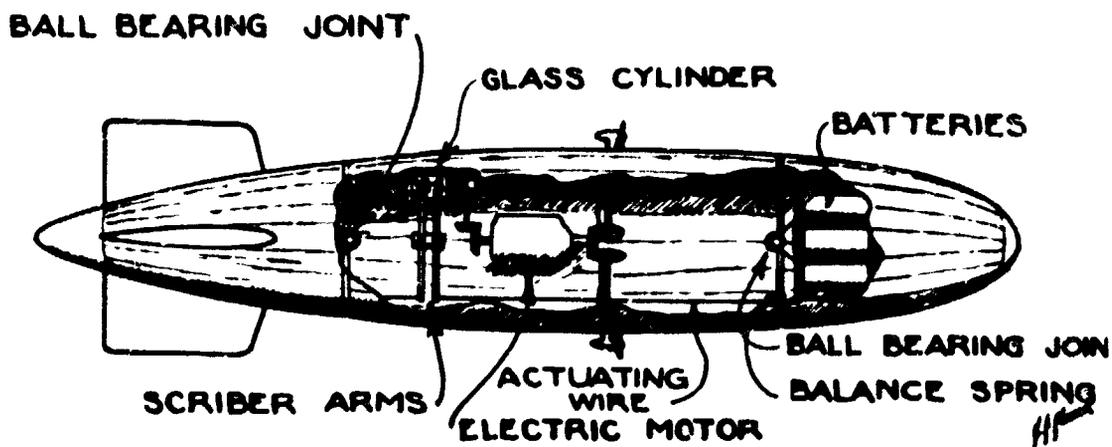
Newer proposed concepts for airships would include hull shapes resembling oblate spheroids, deltoids, or other flattened configurations. These shapes in combination with a large portion of static heaviness may effectively eliminate or reduce the limitation of the ground conditions.

Analysis - The complexity of analysis of the structure of a rigid airship can be illustrated by a statement by C. P. Burgess (Ref. 13).

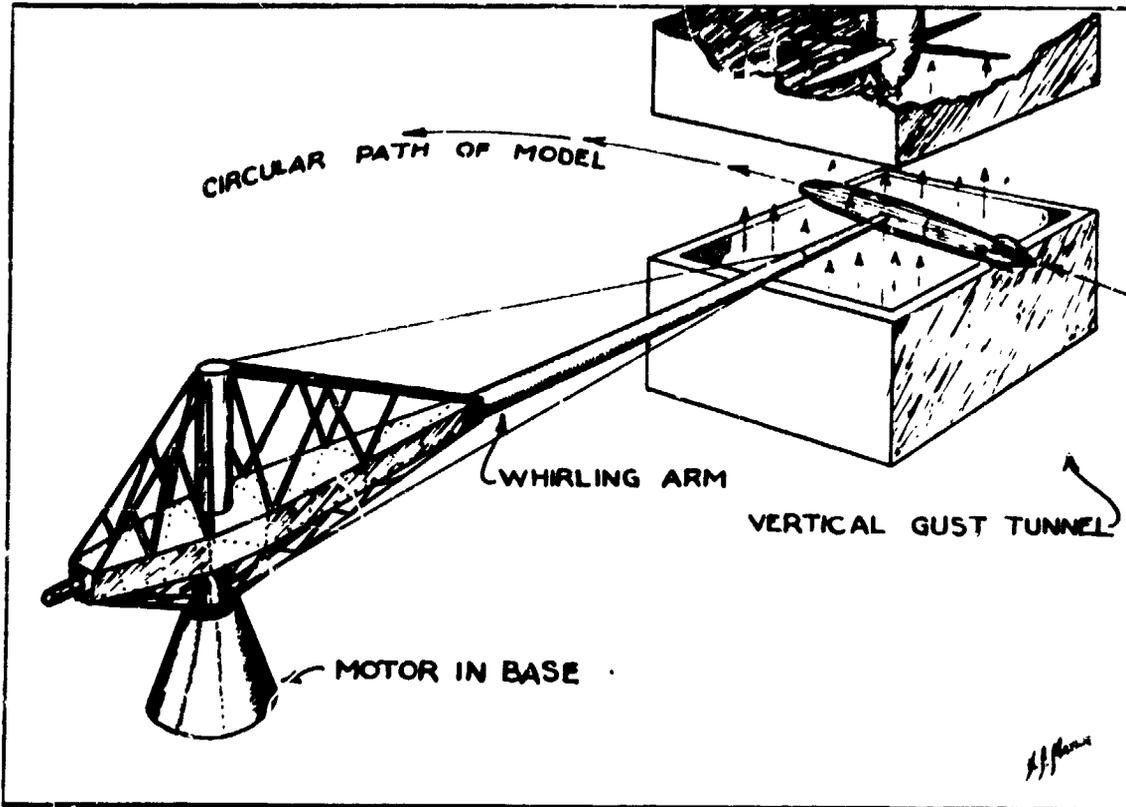
Figure 2



Sketch of Water Channel



Sketch of Water Channel Model



Sketch of Whirling Arm.
Figure 3

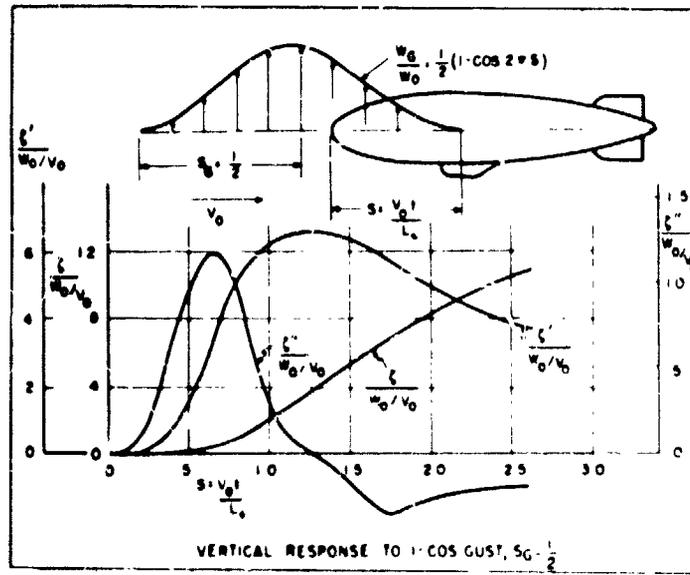


Figure 4

"Even the exact calculation for the simple case of a hexagonal braced structure, five frame spaces in length, and with symmetrical loading, requires the solution of ten simultaneous equations --- with the work carried out to six or seven significant figures".

Of course, no rigid airship was ever built with only six sides so that exact solutions of structural analyses were never feasible for these more complex structures. Approximate methods were developed, however, which have shown remarkable accuracy when compared with later test results (Ref. 14).

Among the contributors to analytical development was Professor William Hovgaard of MIT, who in 1922 developed a method to reconcile two separate approaches involving a bending moment approach and a transverse shear approach (Ref. 15). Later contributions were made by L. H. Donnell, R. V. Southwell, Upson and Klikoff, and Burgess (Ref. 16).

All of these analyses suffered from the inability of the analyst to visualize or separate overall deformation from local effects resulting from the flow of stresses in the structure. An ingenious method for achieving this, using scale structural models, was developed by the Goodyear Zeppelin Corporation based on principles described originally by L. H. Donnell (Ref. 16). This method was applied to both complete and partial models of rigid airships. The essential element in such models was a model girder which scaled down the axial, radial bending and torsional stiffness of the major component members of the prototype. In addition, members also incorporated sensitive means of measuring the corresponding strains and stresses.

The use of these models allowed analysts for the first time to evaluate the existing methods of structural analysis, and separate effects of local from general loads. The design of members was varied according to the type of condition to be investigated. Figure 5a shows a typical member. Figure 5b shows the method of measuring deflections of the model.

These techniques are essentially represented in modern computerized finite element structural analyses. These programs contain libraries of various types of elements such as plates in shear and bending, membranes, rods, beams, rings, etc. whose behavior under various loading conditions are predetermined and their mathematical expressions entered as a permanent part of the computer program. The analyst then represents the actual structure as accurately as possible, using the available elements in the library. A very complex structure can be represented in this fashion, using several thousand elements. The computer program then combines these elements and performs the required structural analysis yielding stresses and deflections for a given load condition, static or dynamic. It also produces mode shapes and frequencies, frequency response or other structural data for which it was designed. The results can be displayed by CRT's or by computerized plotters enabling the engineer to actually see the calculated deformations (Ref. 17). These complex analyses were impossible to perform in the 1930's and it was not until the early 1960's that the high speed digital computer rendered practical solution times ranging from minutes to hours, depending on the problem.

Figure 6 shows a modern aerospace vehicle structure graphically represented in finite element form.

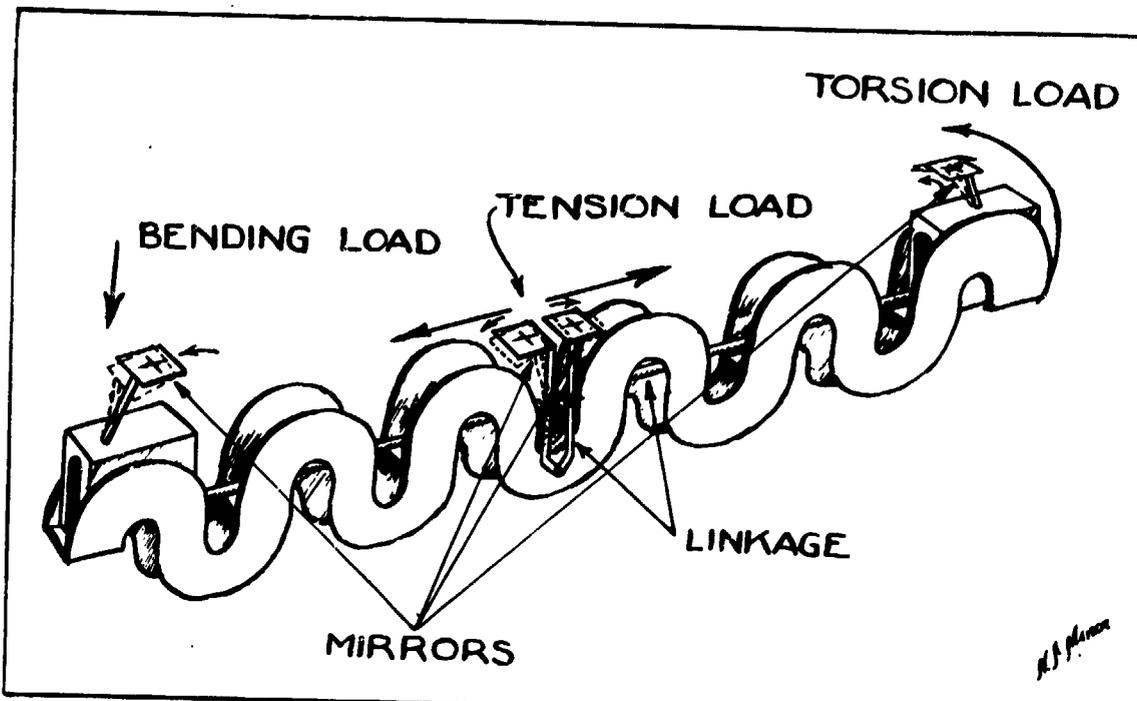


Figure 5a

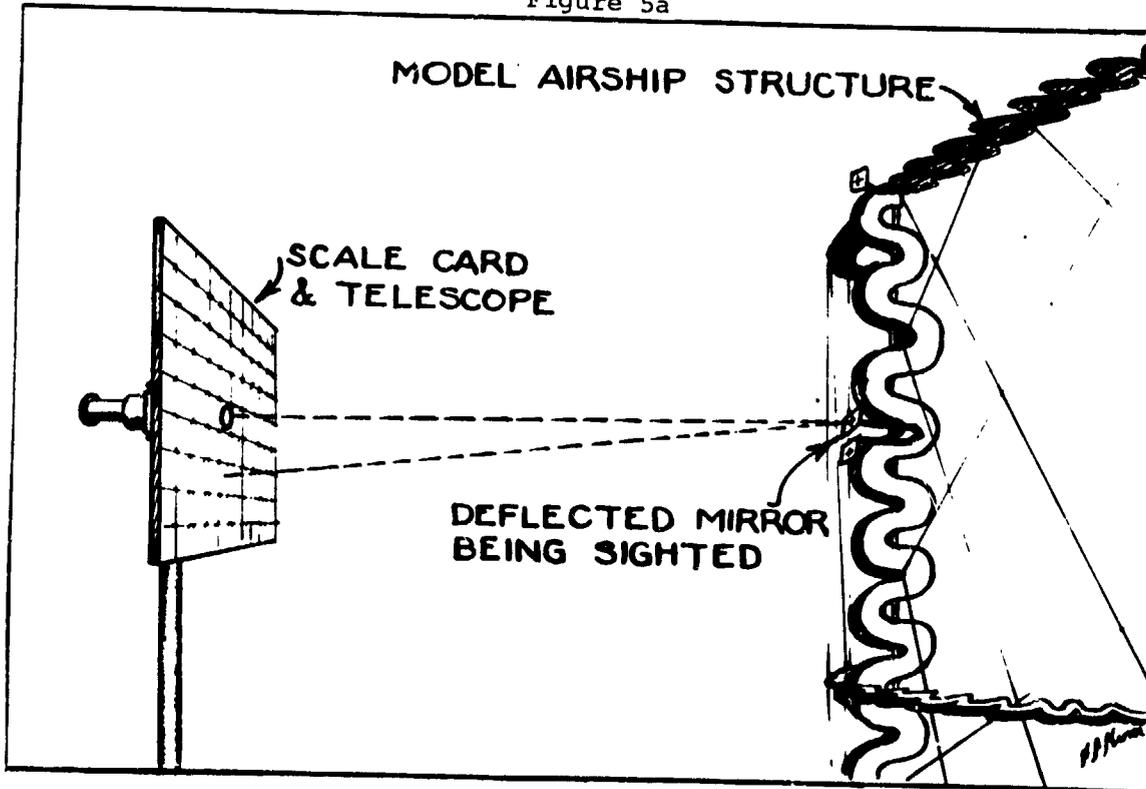


Figure 5b

Testing - There are several categories of tests which all aircraft undergo during development. The first of these is part of a process sometimes called engineering development. In this process, complex structural elements such as joints, typical sections, and members or portions of structures containing advanced manufacturing processes such as bonding are tested to validate the design and analysis approach and the reliability of the manufacturing process. New material combinations are also evaluated to develop, if necessary, design allowables (values of strength and elastic characteristics) which can be relied upon for design. This type of testing would be necessary for any new design.

A second category of testing is the static test, wherein the complete structure, or portions of it, representing the production design are subjected to various load levels up to design limit and finally ultimate or failing loads. While portions of the structure may be tested this way, usually realistic tests of this kind are impractical for large airships. In the past, static bending tests were performed, but only low percentages of the limit could be obtained due to limitations in applying load to the structure.

A similar circumstance was found in dynamic testing of large launch vehicles for spacecraft. Although such tests were conducted, they were limited to input loads of low values. The costs of such testing, which was performed outdoors, was so great as to stimulate R&D programs for developing scaled dynamic test models with sufficient accuracy to replace full scale tests.

Models such as described previously might be adapted for simulating large airship tests as well.

A number of special tests may always be required to check out structural and design characteristics peculiar to airships. Full scale flight tests, of course, will always be required to provide full flight condition check-out for all systems.

DESIGN APPROACHES

Today, there is considerable speculation concerning novel approaches to improved LTA vehicles. These range from proposals for modernized versions of Akron-Macon-Hindenburg designs to types which combine airplane-helicopter-airship features. Much of the technology discussed in the foregoing sections would apply to all types. Improved materials would naturally benefit any aircraft, and may be critical to the success of some. An example of this is the solitary, but significant development of the ZMC-2, an all metal hulled airship. This design was critically dependent on the development of alclad aluminum which provided the difference between achieving a hull where corrosion would have quickly accounted for its integrity and one which remained airworthy for over 10 years, despite its .008 gage skin.

Modern structural design and analysis techniques also apply to all types of future airships. However, there are many distinctions possible among various types proposed and their accompanying structural features and efficiency. The two major classes would include buoyant types and semi-buoyant types.

Buoyant Types

Practically all LTA vehicles built thus far fall into this class. The results of a study by the author made in 1960 showed the rigid non-pressure type to be about 25 - 35 percent more efficient structurally than the non-rigid pressure airship.

Against such efficiency must be weighed other factors such as cost and operational flexibility. Non-rigid envelopes can be fabricated at any suitable facility and shipped anywhere. Navy non-rigid envelopes represented about 10% of the total cost of the airship. Large rigid hulls, on the other hand, must be constructed at the final assembly point with much special equipment and manpower. The structure and the fabrication represent a major portion of the total cost.

Operational flexibility is obtained from the non-rigid by virtue of its envelope being able to temporarily sustain higher than design loads (within limits, of course) without damage. This increases the overall safety of the aircraft and allows for much parameter uncertainty.

Not all of these differences obtain without qualifications. Various methods have been proposed to reduce fabrication costs for rigid types. Composite materials, for example, offer a possibility here due to lower tooling costs. They also would result in further weight reductions over those obtainable from modern metals. Recent NASA studies of transport aircraft have shown structural weight savings up to 30% (Ref. 18). Also, methods may be available to perform the complete assembly of a hull only as a final step (Ref. 19).

While a pressure airship may seem inherently safer, the penalty of assuring an adequate means of sustaining pressure and the need of adjusting and monitoring this pressure almost constantly during flight is an additional operational complexity. The use of compliant materials for structure is definitely a weight penalty as reflected in the study. However, the comparison does not include application of recently developed fibers. Compartmentation of gas space in a non-rigid does not produce the same advantages as available to rigid. A high rate of pressure reduction is an unacceptable hazard to non-rigids.

The metal-clad airship would show an improvement over the values for the non-rigid. Modern versions of this type (in large sizes) constructed of high strength aluminum, stainless steel, or titanium might equal the rigid in structural efficiency, although other design trade-offs might auger against the choice.

A design concept which combines a rigid/non-rigid concept was invented by C. P. Burgess, but never applied in practice (Ref. 20). The main structure consists of four longitudinal keels connected by widely spaced transverse frames and diagonal shear wires. Only the shear wires are inside the gas space. The gas is contained in a combination envelope-cover similar to a non-rigid airship. The keels are external to this envelope and are faired over by a light cloth cover. The combination envelope-cover is terminated by semi-hemispherical or concave ends with the space between cells also filled with gas. Ballonets are used to pressurize the gas sufficiently to maintain a stiff outer shape. These features are shown in Figure 7. As pointed out by the inventor himself (Ref. 21), there are a number of advantages and disadvantages to this concept.

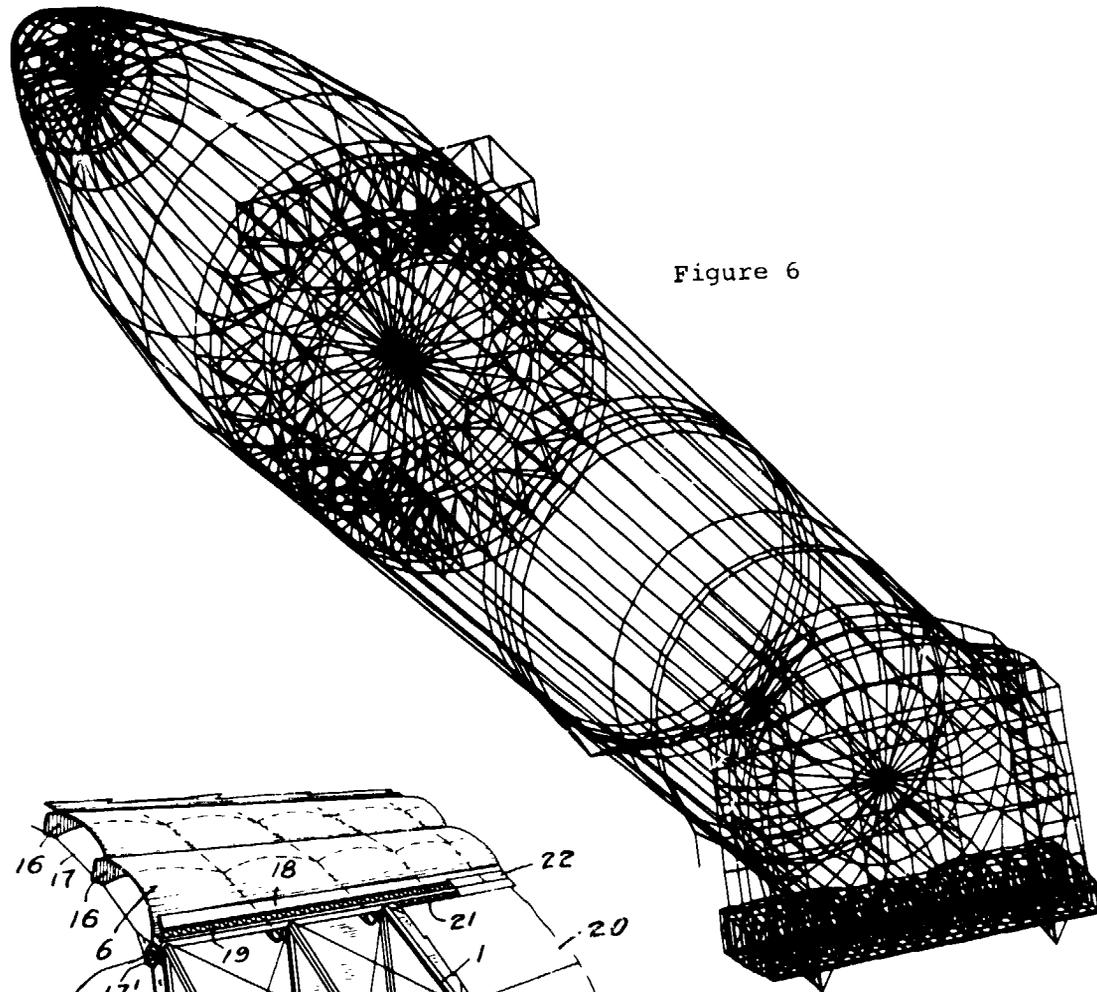


Figure 6

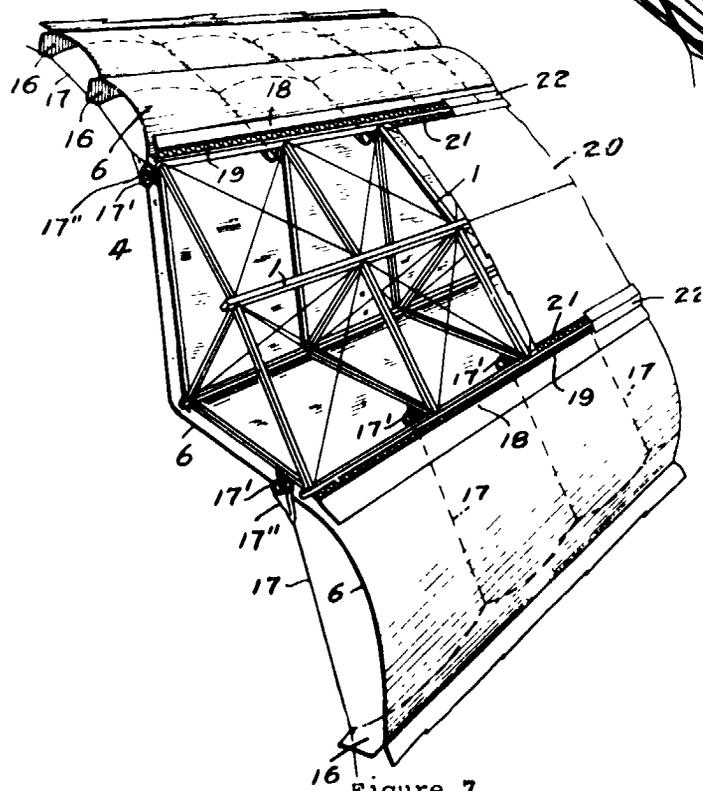


Figure 7

Semi-Buoyant Types

Although semi-buoyant LTA aircraft would acquire some of the characteristics of airplanes or helicopters, they will have structural indices (Ref. 22) considerably below ordinary HTA aircraft. Therefore, they will not be entirely free of the need to utilize ultra-light-weight structure. Single skin construction would appear to be limited to pressurized hulls unless the permissible operating speed ranges are significantly high enough to allow skin gages or semi-monocoque construction of sufficient stiffness to avoid local buckling. Perhaps the higher modulus composite materials would provide the answer here.

As noted in the introduction, gas retention will require consideration of the same factors as were necessary for buoyant types. Thus, most of the materials technology can be applied.

There is a substantial base technology for the aerodynamics of ellipsoidal hulls. A similar technology might be extrapolated from tests of certain aircraft body shapes such as lifting bodies and re-entry shapes. The size difference could produce serious discrepancies in drag and stability estimates, but should not be too serious for loads determination.

PROBLEM AREAS

Materials

Fortunately, the high altitude free balloon and the tethered balloon have continued to develop a technology in materials which can be applied to future airships. This includes the art of design and fabrication of pliant materials. A similar development does not really exist for rigid structures. Ultra-lightweight metal design and fabrication has not been needed for aircraft and only to a limited extent for spacecraft. Whatever technology is available in this regard may well come from the latter engineering activity, however. Composite materials offer a distinct possibility for improvements, but most of the research and design activity has been directed toward airplane application. Only recently has there been recognized a need for large area structures with low unit loads for space application. This is an area requiring a combination of advanced structural concepts and new materials applications and could represent a fairly large technology effort in LTA.

Structures

The area of structural analysis has received sufficient attention in recent years such that much of it is applicable to the most complex airship structure and should be no great problem for the future. The area of weakness, however, is in the determination of loads. This was never satisfactorily achieved for conventional airships, even though progress was made as previously noted when gust transit criteria became predominant in design. Much more needs to be accomplished here, particularly in relating realistic conditions to loads in very large vehicles. An important part of this relationship is the response of the airship to the air load condition in terms of the overall vehicle dynamics and control activity. Practically no technology base exists in this category. Likewise, a technology program would have to be established for new configurations.

The success or failure of either buoyant or semi-buoyant vehicles will be dependent on their overall efficiency and cost. Both elements will be strongly influenced by conceptual innovation and application.

of superior design techniques. As was true in the 1920's and 30's, the best engineering talent may be required to achieve feasibility and ultimate success in new future vehicles.

CONCLUSIONS

1. Both buoyant and semi-buoyant airships have common materials and structures requirements in terms of needs for pliant materials, pressure control, and lightweight structural design.
2. Pliant materials technology can be applied from present balloon development to design of gas cells and envelopes and should result in higher efficiency components.
3. Improved metals and composite materials both offer reductions in overall weight for future airships.
4. Loads determination in large airships represent a critical technology need for structural design.
5. Modern computer techniques will provide a significant improvement in analysis of complex airship structures.
6. Testing of large scale airship structures will probably require use of models.
7. New design concepts are needed for most effective combination of structures and materials technology.

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